THE USE OF LINES OF NONEXTENSION TO IMPROVE MOBILITY IN FULL-PRESSURE SUITS

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FOREWORD

This study was initiated by the Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The research was conducted by the Rand Development Corporation of Cleveland, Ohio under Contract No. AF 33(657) -10992 from March 1963 to March 1964.

Mr. Arthur S. Iberall, Chief Physicist, was the principal investigator for the Rand Development Corporation. Mr. Kenneth W. Kennedy of the Anthropology Branch, Human Engineering Division, was the contract monitor for the Aerospace Medical Research Laboratories. The work was performed in support of Project No. 7184, "Human Performance in Advanced Systems," and Task No. 718408, "Anthropology for Design."

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This technical report has been reviewed and is approved.

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ABSTRACT

An important objective in the development of a full-pressure suit for a human being is to permit the wearer full mobility without interfering with physical capability. Although the human skin is stretched during body motion, there is virtually no stretch along certain lines, here called "lines of nonextension". This investigation was undertaken to determine the efficacy of utilizing lines of nonextension to provide natural mobility and minimal ballooning in full-pressure suits. The program of investigation pursued was: (1) to map out these lines of nonextension, (2) to test whether string elements of high elastic modulus, a connected network, could be laid along these lines of nonextension without providing any constraint to mobility, (3) to obtain a highly mobile pressure-retaining layer to be constrained by the net, and (4) to construct and demonstrate an entire pressure-retaining garment system that makes use of all necessary layers and string elements in a completely connected, netted covering for the body, with minimal constraint to mobility up to 5 psi. The technique, result, and collateral observations relevant to each of these phases are described. A mobile, pressure-retaining garment was developed by building each structural, functional layer into the composite garment in accordance with the basic design theory.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

This study tests the applicability of a certain set of ideas, which are based on observed scientific fact, to the engineering problem of building a pressure suit that permits full body mobility while pressurized or not.

The following description is a brief summary of these ideas:

Since the human body tends to retain its form, taking no appreciable "set" after ordinary body deformations, its behavior is expected to conform to the laws of physical elasticity. Deformations in an elastic body are described by the strain ellipsoid, in which a small sphere of material deforms to nearly ellipsoidal shape under elastic deformation of the entire body. On the surface of such an elastic body, the projected deformations transform a small circle into an ellipse. Since all points on the ellipse are derived from points on the undeformed circle, in general, there may be two diameters in the ellipse that are not stretched. (They may be noted by superimposing the original circle on the deformed ellipse.) An extension and connection of these radial directions may be referred to as a mapping of the surface of the elastic body by "lines of nonextension." Such a theory is expected to be applicable to the surface of the human body. If so, high strength strands of material may be laid along these directions and joined at their interstices for free-rotation capability. These strands can then carry loads developed by the pressure forces transmitted against the strands, without interfering with mobile deformations of the body.

A more complete discussion of the background theory and its application to full-pressure suit mobility is found in reports by Iberall (refs 1 and 2).

EXPERIMENTAL INVESTIGATION

MAPPING OF LINES OF NONEXTENSION

Lines of nonextension on the body were determined as follows: A 1-inch ink circle was stamped at a particular location on the subject's skin. He was then asked to move (deform the skin of) that body region. According to the theory of elasticity, a small circle on a body surface during an elastic displacement will deform into an ellipse. This is the result for body deformations as illustrated in figure 1.

Figure 1

Distortions of a Circle on the Skin to Near-Elliptic Form

Figure 2

Development of a family of lines of nonextension from the unchanging radii of the deformation ellipses

If the deformations involve only small strains, there are generally two diameters with unchanged lengths in the ellipse. These two diameters can be discovered by applying a 1-inch caliper to the ellipse, or by restamping the original circle over the ellipse to discover the intersections. These two diameters, when the original circle is transformed to the new ellipse, have not stretched, but have only rotated (and perhaps warped a little). Therefore, they represent a mapping of a two-fold family of directions, along which no extension has taken place at that point on the body. By continued point-to-point mapping on the body, a completely connected network of directions can be found which forms a system of lines of nonextension of the body for that particular deformation. The body, however, is articulated internally, with its softer elastic parts mounted on an essentially rigid skeletal frame. Experimental study of the intrinsically limited motion at each joint verifies that this system of lines of nonextension will be essentially the same for all deformations. Thus, in practice, the lines of nonextension are mapped by seeking

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extreme deformation positions for each point of the body, so that the circle will be stamped in a position in which length on the skin is most foreshortened in some direction, and the ellipse will be noted in another position in which the skin is most elongated in some other direction. The lines of nonextension thus determined from such extremes will then be found essentially valid for any intermediate deformations.

How an entire network of such lines of nonextension is generated from the deformation ellipses is illustrated in figure 2.

Such a system has been carried from region to region, all over the body. There are a few moderate defects in the developing scheme. First, as lines are extended farther and farther along the mapping field, small errors that might be incurred accumulate so that one cannot be certain how much he has strayed from the particular line of nonextension that he may be following. Second, there are lines in critical regions with a very small angle of separation. Both cases lead to divergence between a true line of nonextension and the experimental estimated line. (The errors are not at a given point, but are propagated as one follows a line of nonextension farther and farther away from a given point.) To refine the estimates, one major technique that was used, a technique that fits an operational definition of what a line of nonextension is supposed to be, was to trace the line with an inextensible "string" to demonstrate, in fact, that no essential extension existed along the experimental lines. Such strings were then used to refine the longer-range extrapolations. See figure 3.

Figure 3

Checking the system of lines of nonextension by inextensible "strings"

These data, acquired region by region from a test subject, were transferred to a sizing manikin. The sizing manikin is a three-dimensional embodiment of dimensions for the Medium Regular size of the USAF 8-size, Height-Weight sizing

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system (refs 3,4). The system of lines thus developed is shown in figures 4 and 5 for the upper and lower parts of the body.

This final mapping placed on the anthropometric manikin was obtained by transfer from three human subjects. Their heights and weights are listed below:

TABLE I

DIMENSIONS OF THREE SUBJECTS USED
IN DETERMINATION OF LINES OF NONEXTENSION

Subject	Height (inches)	Weight (lbs)
A	65.0	150
B	68.5	160
C	70.5	180

The problem of developing a pressure-retaining, form-fitting garment that reflects these lines of nonextension can best be understood by reference to figure 6. This figure depicts an experimental mapping of lines of nonextension with inextensible netted material at two different stages of fitting. The one on the left is illustrative of a preliminary fitting stage, in which a rather coarse mesh of no great strength is used to outline the garment patterns. The one on the right shows a more advanced fitting stage, in which a closer mesh of appropriate high-strength Dacron netting material is used.

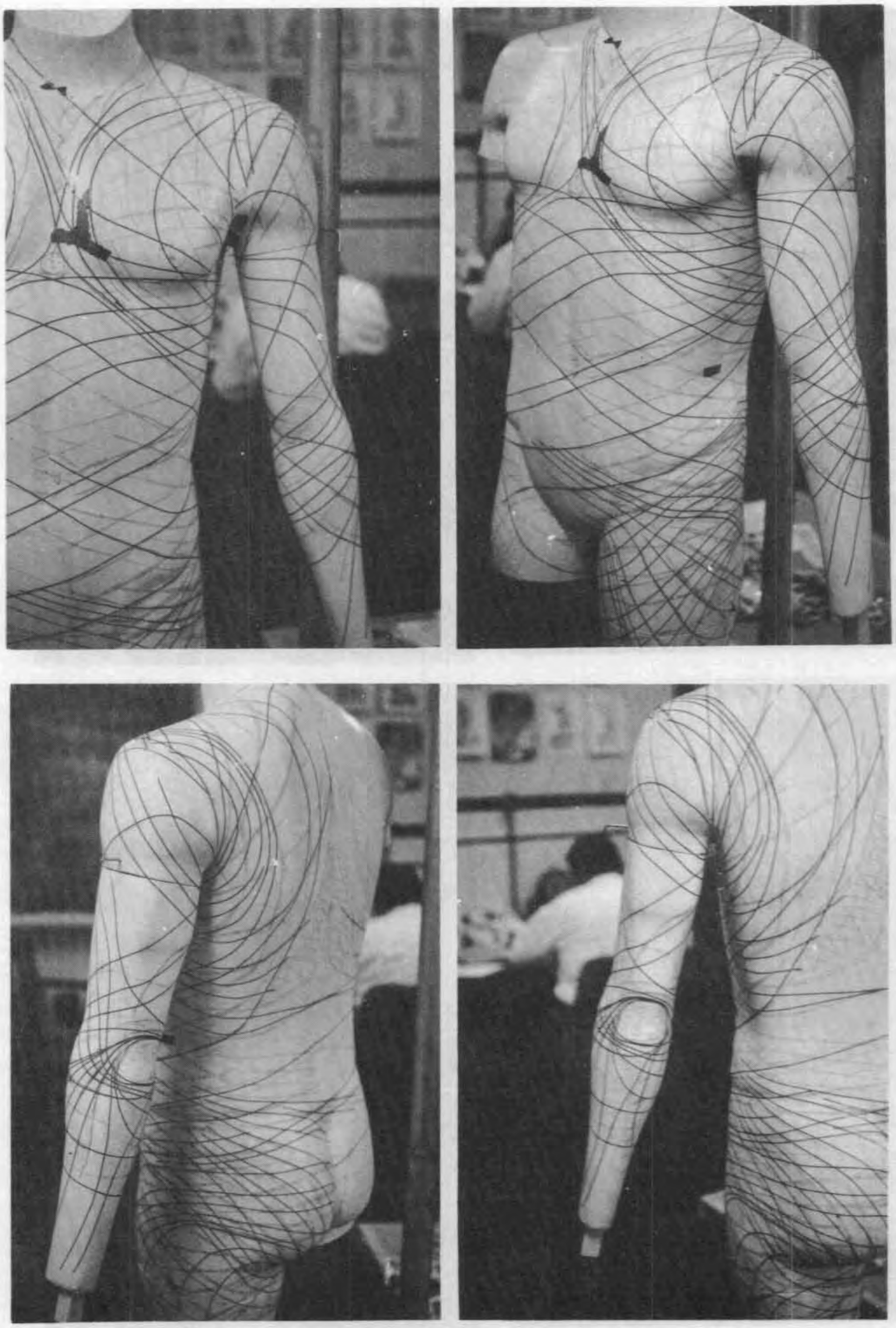

Figure 4

Lines of nonextension for the upper part of the body

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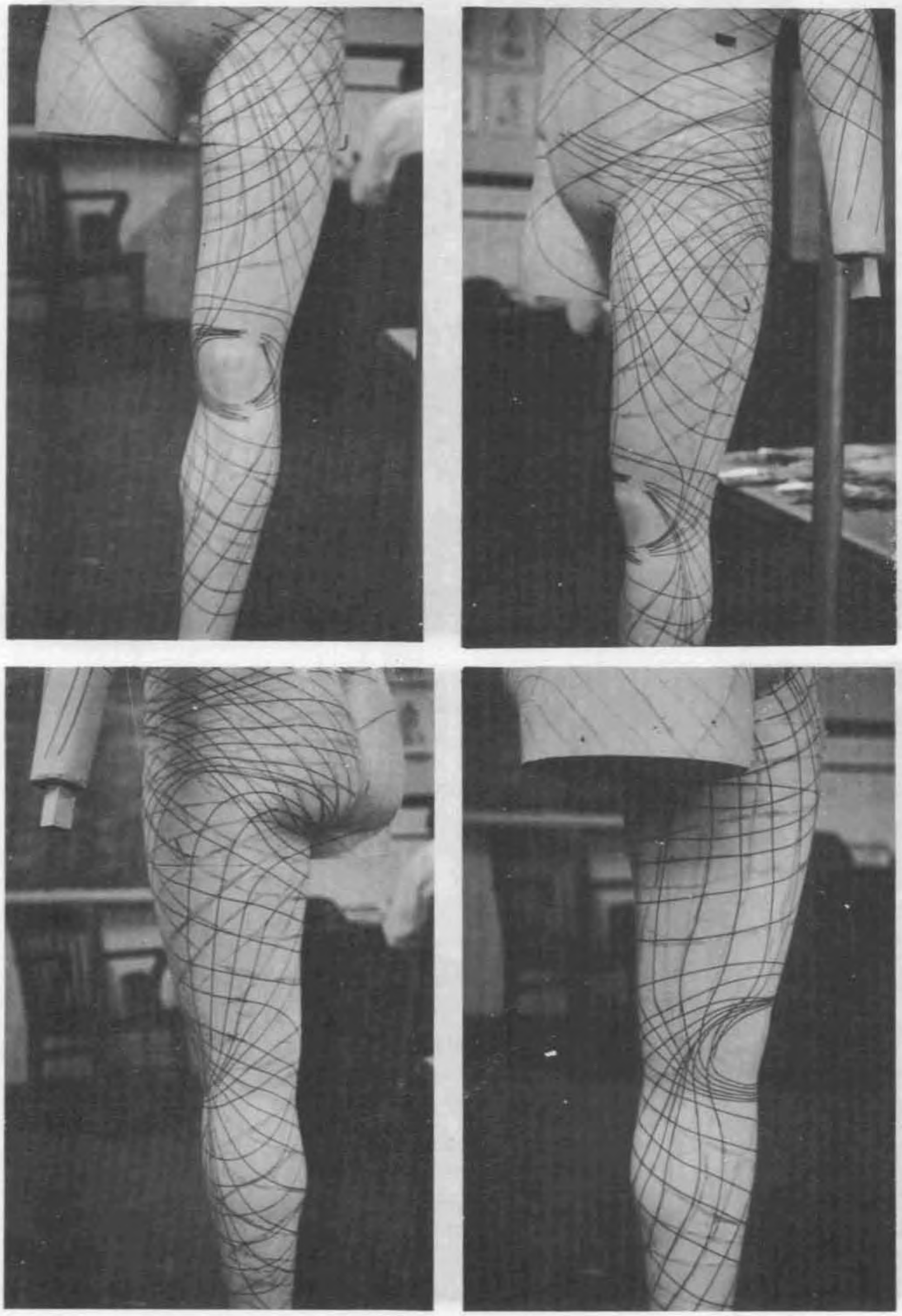

Figure 5

Lines of nonextension for the lower part of the body

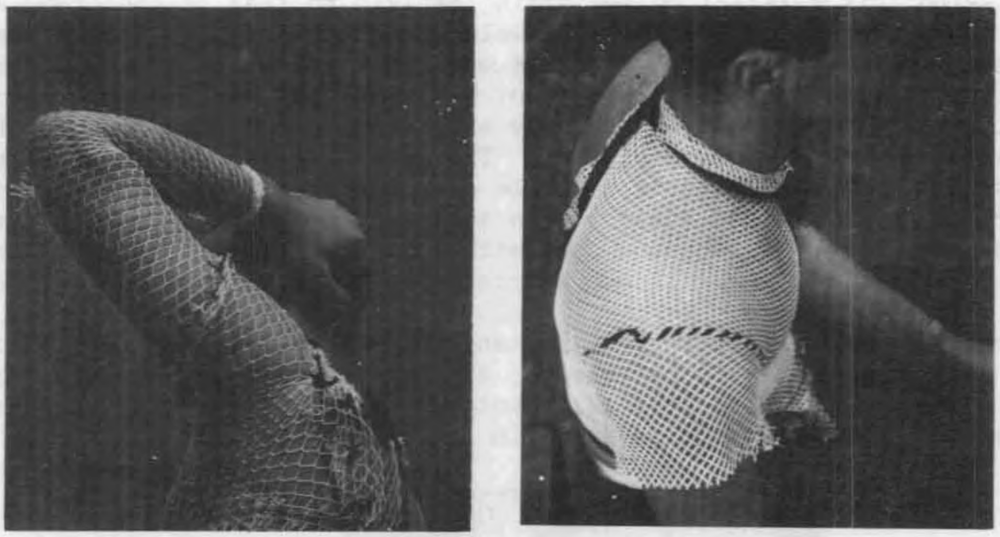

Figure 6

Two stages in the transfer of lines of nonextension to a homoform covering of the body with inextensible netting materials

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DEVELOPMENT OF A LOAD-BEARING NET LAYER

The material chosen for the load-bearing layer of net for the demonstration pressure suit is a woven Dacron net with four diamonds to the inch. The individual diamond strands consist of 5000-denier, high-strength, heat-stretched Dacron. Each strand has a breaking-strength in the range of 50 to 100 pounds.

By laying this material on the sizing manikin so that it conformed with the lines of nonextension, patterns were developed which tended to follow the lines of nonextension in every region. While one might visualize the need for a perfect conformity with the lines to prevent any wrinkling or constraint during motion, investigation revealed that only a reasonable approximation to the lines is necessary to permit ample mobility. The novel aspect of this particular program phase was that the patterns could be developed fully on the dummy without further recourse to a human subject. In the past, only approximations for netting each joint were available. Now, with data recorded on a sizing manikin (figs 4, 5), data from the full body surface are available for patterning.

In removing the patterns from the manikin and transferring them to a human subject, they needed only to be taken up at their borders to meet the more specific sizing need of the particular subject. Such a garment in an intermediate state of construction is shown in figure 7.

Figure 7

Net load-bearing layer transferred from manikin to human

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The generality of the solution was illustrated by transferring such garments to all three subjects, who found themselves capable of the same general body mobility, although with some differences in general garment conformity. In anticipation of sizing questions, the opinion was expressed that the general enclosed body volume will show much less variation from person to person than size or height variations may suggest, and that the major differences between sizes may be those involving arm and leg segment lengths. The experiments conducted with this general suit solution support this opinion.

Although still pictures cannot depict the quality of response in this type of covering, one may summarize the statements of those who have worn the various examples of net suit. The garment leaves the wearer with a sense of its presence at all times, even under pressure, but without any noticeable constraint to any body movement, and with no bunching of the material. The garment feels like a second skin that conforms to the body and that deforms naturally with the body. Even though the material is nonextensible, the garment feels like a stretchy garment that completely conforms to the body by stretching and shrinking without wrinkling. The difference between the two garments is that the lines-of-nonextension garment, made of inextensible materials, can carry high surface stresses in the plane of the netting.

It is this property of permitting deformation while carrying a high load, that is, the load developed by the internal pressure applied to a pressure-retaining layer, that makes this solution unique and suitable for development in a pressure suit.

DEVELOPMENT OF A PRESSURE-RETAINING RUBBER LAYER

While the net material can carry load and can permit mobility, it cannot retain air under pressure. For this, an impervious but very stretchy layer is needed. If one wishes to explore the degree of stretchiness that is required to permit complete body mobility in a conformal covering, one may cover the entire body with an elastomeric material and vary the thickness to find out the point at which a wearer considers the burden undesirable. The material property that governs the loading is the product of the tensile modulus and thickness of material.

For latex rubber, a thickness of 0.002-inch is almost unnoticeable, 0.005-inch is quite comfortable, 0.010-inch acceptable, 0.015-inch tolerable, and 0.025-inch is uncomfortable. This may be summarized (as a satisfactory range for the pertinent material property) by the spring rate, i.e. the stretching force necessary to double the length of a 1-inch-wide strip of material. Assuming an elastic modulus for rubber of about 100 psi, these rubber thicknesses correspond to spring rates, or stretch forces of 0.2, 0.5, 1, 1.5, and 2.5 pounds, respectively. Thus, it is believed comfortable to tug material covering the body when the resisting forces are about 0.5 to 1.5 pounds per inch of width per 100% elongation. To provide a frame of reference, such rubber suits are similar to the restraint offered by a pair of dancer's leotards, being quite comparable with the thinner suits and perhaps twice as resistant with the thicker suits.

Rubber suits of about 0.012-inch thickness were obtained and used in the course of this development. They were made by being dipped on a full human form. Figure 8 shows an example of such a suit.

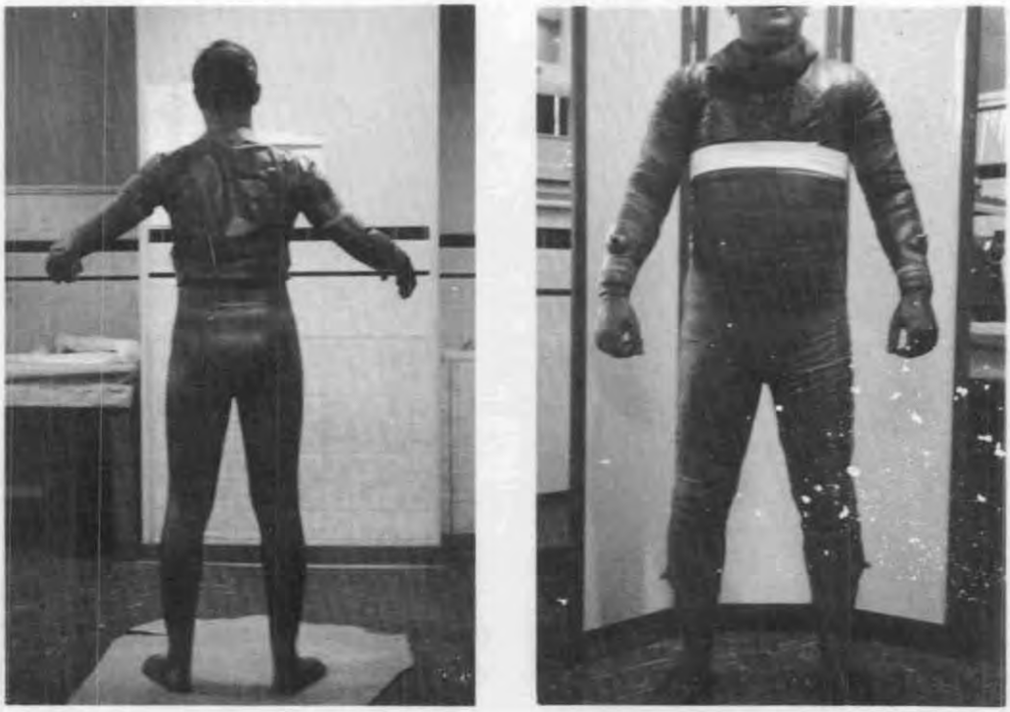

Figure 8

Two-piece form-fitting rubber suit

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The suit is dipped in four pieces: a lower section, an upper section, and two arm sections which are then cemented to the upper section.

While a number of brief experimental efforts was made to develop a strong membrane, such as a stretchy, highly puckered or crepe-rubber coated material that would permit low stretching forces in a single layer of a strong impervious material, no satisfactory answer was found. A 0.012-inch rubber suit with a leotard covering over it was more comfortable and had greater strength than any rubber-fabric combination that could be devised. Since such a development was not a major objective of this contract, the efforts were discontinued and the thin impervious rubber suit covered with a leotard was chosen for demonstration purposes.

This combination is shown in figure 9. A secondary function assigned to this leotard covering is that it should permit a mild slipping action to take up any small lack of conformity that might occur between the skin and the nearly nonslipping net.

Figure 9

Rubber suit covered by a leotard for protection and to perform as a slip layer

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DEVELOPMENT OF A VENT LAYER

The combination of the items of a pressure-retaining layer and a net layer may be satisfactory to provide pressure retention, mobility, and load-bearing under pressure. However, it is not sufficient to provide thermal comfort. There are two requirements posed by a complete and closely conformal covering for a human body; the first is that the pressure should be equalized all over the body during body deformation; and the second is that the suit should be ventilated to remove heat. Both an air heat-exchanger and a liquid heat-exchanger were explored in the 1950 development. An air heat-exchanger was used in the 1958 development. In the latter development, an Air Force ventilating suit was made available and modified for the purpose.

The project officer of the current effort expressed the opinion that the vent suits available at the time might compromise the aims of this investigation. He therefore asked that a compatible vent suit of minimum complexity be constructed.

This development was undertaken to further demonstrate the value of the concept of lines of nonextension. This concept could be used to guide the development of a conformal spacing garment, even if fairly rigid as a spacer, if the construction material had the net-like property of rotation of its "diamonds" at the interstices. A porous or fibrous spacer material was used to construct the vent garment.

A vent suit utilizing these materials is shown in figure 10. It has been found that reasonably adequate conformity to the lines of nonextension can be produced in such materials with very few pattern pieces, that the garment is quite mobile, that the material can stand up under considerable abuse, that it has performed its pressure equalizing function well, and that it has demonstrated some unexpected but useful heat-exchange properties.

Figure 10

Vent suit made from an industrial spacer material

The vent garment is worn over a leotard underwear layer. The underwear layer is necessary to hold perspiration and to prevent body chafing. The rubber suit is worn over the vent suit. A leotard is worn over the rubber suit as a rubber protecting layer and as a slip layer.

It was found that, even though unvented at room temperature with his head uncovered, the subject remained comfortable for periods up to 5 hours in the vent and rubber suits. When the rubber suit was removed, there was considerable water in the porous Trilok layer and condensed on the inside surface of the rubber. However, the leotards underneath were essentially dry. On the other hand, small portions of the underwear not covered by the vent suit were quite wet. Apparently, this vent layer sets up a

strong convection in the nonhomogeneous micro-atmosphere from the skin to the rubber suit, with condensation of moisture on the outermost, cooler layer. When ventilated, all body surfaces remained essentially dry.

As a spacer to provide air distribution, the material served well. Concentrations of body weight in small areas, as in sitting, and extreme flexion of body segments such as the knees and elbows did not pinch off any segment of the distribution system.

To assure a scrupulously valid demonstration of suit mobility, it was essential to guarantee, even more completely, that there was little pressure change around the body during body movement. Thus, an external distribution system of 3/8-inch ID tubes connected into the rubber suit were used to equalize the pressure. These were attached to openings at the chest, both ankles, both wrists, and in the helmet. The pressure variation around the body is estimated at 2 to 5 inches of water.

DEVELOPMENT OF A LONGITUDINAL RESTRAINT LAYER

The combination of a pressure-retaining layer, a net layer, and a venting layer may permit mobility, thermal comfort, and uniformity of pressure in a pressure suit, both inflated and uninflated; but like all suits when pressurized, will still show the defect of an unacceptable longitudinal extension. The background of ideas involved in solving this problem is significant.

Although the use of the lines of nonextension permits mobility while providing a mechanism for carrying loads, it does not follow that all of the load-bearing capability is applicable to accomplish fully the desired end of keeping a local patch of netting close to the patch of skin to which it is supposed to conform. Much of the technical background of this problem has been discussed previously (ref 2).

The particular difficulties include the possibility of bulging of elliptical to circular cross sections which moves the patch away from the skin, and a possibility of "elongation" which moves the patch along the body axis. Circumferential extension is not a problem. (Nonstretching strings following the lines of nonextension assure that there will be no circumferential extension.)

Thus in the early 1950 development (ref 1), these difficulties were explored by the following two techniques (the difficulties were not completely understood at that time). If an all-net suit bulges, it may be restrained in regions between joints: regions in which only limited deformation capability exists. (Note that the skeletal structure in humans lends assurance that many regions of the body act like rigid bodies.) A leather-like restraint was used first. It did not appear to be adequate to restrain the bulging at that time. Therefore, rigid sections were tried instead. They eliminated the bulging problem and lessened most of the longitudinal extension problem. However, an extension of perhaps 1 to 2 inches remained in the overall 70-inch length.

The possibility of transmitting loads using available nets other than those following lines of nonextension was explored. Several types of net were developed. Besides nonslip knotted netting that followed the lines of nonextension, other mapping nets developed were "slip" nets which take advantage of the ability of map curved--surfaces with ruled line elements (such properties lie within the field of topology in mathematics) to permit certain prescribed motions; namely, to provide bending freedom, or rotational freedom at a joint by some nets of a nonknotted form; and some examples of nets that permit substantial increase of area during deformation. The latter may be useful on limited body surfaces in which the deformation ellipse is larger than the undeformed circle. However, the choice of the net type during various suit demonstrations was always a matter of convenience and has been in flux.

In the 1958 development (ref 2), the investigation started with the type of rigid restraints previously used, and approximate lines of nonextension nets at the joints. It became quite clear at that time that longitudinal restraint was probably a more serious problem than bulging. To limit the longitudinal elongation to perhaps 1 inch at 5 psi, for the major lengths from the mid-chest outward to the extremities, an inordinately tight lacing had to be used in the nets. The true source of this elongation was not really understood, but it

was not proportional to pressure as one might expect of an elastic stretch.

The rigid longitudinal restraint was modified to a cloth-like constraint to determine if bulging really was a problem, and a multiplicity of net layers, four altogether, was used to determine if net yield was a problem. Bulging was of little concern in mobility, but there was no intrinsic reduction in elongation. It was clear that the elongation took place with the initial application of pressure load, and then remained essentially unchanged. It was also clear, however, that complete mobility required utilizing the whole system of lines of nonextension rather than portions in limited regions. Thus, in a second modification, there was time only to quickly make a net suit based on an approximation, using only a two-piece front-and-back pattern. In modification we again used rigid parts for an independent longitudinal constraint. There was time, however, to relax the rigid constraint in the chest. Finally, the concept of the last necessary major element for suits emerged.

The lines of nonextension generally form a much shallower angle with the longitudinal body axis than does a string element that will support the circumferential stresses and the longitudinal forces. The equilibrium angle for a net restraining a pressurized cylinder is about 35°. The lines of nonextension tend more toward 25°. Thus, if the total pressure suit enclosure is pressurized, the forces tend to try to rotate a near 25° angle out to near 35°. This is the source of elongation. (See ref 2.) If the lines of nonextension are laced on a nearly rigid body (such as an articulated doll), the elongation can be prevented by tight lacing. It was this type of solution that had reduced the longitudinal elongation in some of the previous efforts. Once the problem was understood, a relatively simple solution offered itself: confine the body, not by a single net layer that either follows the lines of nonextension in a nonslip knotted net, or by a restraining slip net, but by a combination of both. The lines of nonextension permit mobility and provide, in the main, the circumferential load-bearing and some of the longitudinal load-bearing. The longitudinal restraining slip-net provides the longitudinal load-bearing, without limiting the large joint mobility that it is designed to retain.

Thus, in the second modification in 1958 (ref 2), longitudinal constraint consisted of a cloth-like chest covering, rigid coverings over the pelvis, thighs, legs, upper arms, forearms, and head, with slip-net lacing between pants and vest sections, pants and thigh sections, and chest and upper arm sections. This longitudinal restraint layer was applied over, and independently of, an underlying lines-of-nonextension net suit.

In the present development, it was possible to design a net suit rationally by approximating a complete set of lines of nonextension, rather than by hasty improvisations. The advantages emerged in the rationality and ease of patterning a net suit and in searching out any pattern improvements that were needed when minor mobility defects made themselves evident. Patterning errors in the net suit did not become evident until the entire garment was assembled and ready for pressurization.

It was now possible to relax the covering requirements for longitudinal restraint to what appeared to be a minimal constraint. Thus, for this phase of study, it was decided to try a cloth restraint over only the chest and pelvis, with a slip-net connecting the two.

The construction of this layer is shown in figure 11.

Figure 11

Longitudinal constraint layer
over the chest and pelvis,
connected by a slip-net

To understand the support system, note that the underlying net system takes the circumferential loads, and the slip-net system, nominally of 45° angle, permits complete waist mobility but prevents longitudinal extension.

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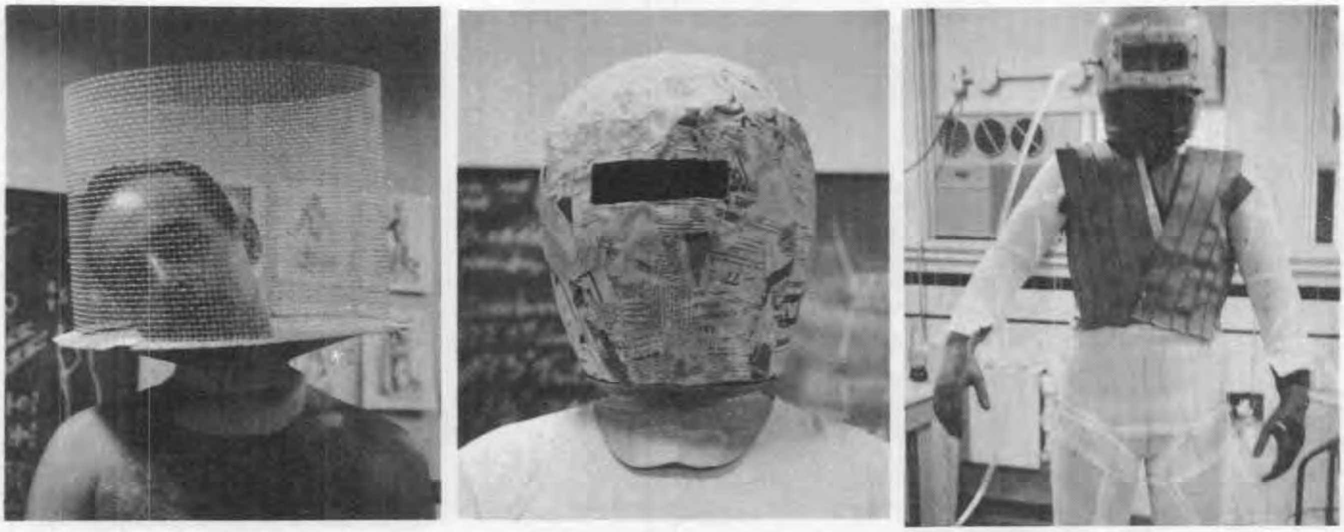
DEVELOPMENT OF A RIGID HELMET

To avoid compromising the demonstration of shoulder mobility, a fixed rigid helmet was developed. The helmet permitted minimal head mobility inside the helmet; yet did not interfere excessively with shoulder motion. Note, however, that full mobility of head and shoulder can be provided by using the lines of nonextension over the neck. Should there be individual objection to neck constraints, however, some loss in mobility would have to be accepted in either the head or the shoulder by the use of a fixed helmet.

The design philosophy used in the helmet is shown in figure 12. It is based on the concept of allowing a reasonable division of the external space between head and shoulder for the mobility requirements of each. The helmet, which fixedly divides the space available to the head and acts as a stop to the shoulder, is designed to permit mobility of the head within the helmet.



a. Determining the Cone of Freedom of a Rigid Helmet

b. Forming the Helmet Shape

c. Providing Helmet Hold-down by Longitudinal Restraint Layer

Figure 12

Three Phases in the Development of a Rigid Helmet

A wire-mesh frame attached to a neck support collar permitted designing for a reasonable cone of freedom for the head, within a fixed helmet. This cone, rounded off at the top, was then molded in papier-mache, and then in a fiberglas-polyester shell. No particular refinements were designed into the helmet shell, except to provide visibility for the subject. A simple but quite effective neck seal was designed. (The rubber suit was simply pulled over a pair of rubber O-rings in the rim at the base of the helmet. Another ring was then pulled down over the rubber and into the depression between those on the helmet.) The helmet opening is minimal for a slip-on helmet, having about 7-inch lateral opening, and 9-inch fore-and-aft opening.

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The fastening for the helmet is essentially a tie to the net suit and the hold-down of the net suit by the longitudinal restraint layer garment. The tie consists of a net laced around the helmet, which is held in place by two external steel bands. Figure 12c shows the rubber suit pulled up over the helmet and shows the uncompleted upper longitudinal restraint. In the final model, the visual opening was enlarged to give the subject greater field of view.

ACCESSORIES

The suit was completed with the following items:

Shoes were simply a pair of high-laced, rugged work shoes.

No special provision existed for any detailed hand solution. Thus, a very simple application of the lines of nonextension to the hands was used. Since the number of joints in the hands is considerable, it would take almost as much detailing for an extremely mobile hand as for an entire body. This was impractical within the existing scope and time of this contract. However, since the body of the hand is a relatively flat segment, it is essential that a rigid constraint be used over the palm to prevent bulging.

The degree of detailing that was provided in the gloves was sufficient to permit, even in these relatively undeveloped gloves, good hand mobility. For example, it was possible for the subject to write while pressurized, to handle tools, and to do fairly small coordinated tasks.

Pressure outlets were provided in the rubber suit at the shins and in the forearms. These consisted of internal stand-offs, to prevent blockage, and of tubes with 5/16-inch ID. A main suit inlet, a tube with 11/16-inch ID, was provided in the chest region. Two 1/8-inch standard pipe outlets were provided in the helmet.

These outlets were interconnected and supplied as follows: A large capacity, two--stage, tank-pressure regulator (inlet, 50 to 2000 psi; outlet, adjustable 0 to 30 psi) supplied breathing-quality air through a 3/4-inch ID hose to the main suit inlet. A tee at the suit provided a direct path to one of the helmet inlets through a 5/16-inch ID plastic tube. Identical plastic tubes collected vent air from the helmet, the two forearm stations, and the two shin stations, and was exhausted through a 3/4-inch ID tube to a 3/4-inch valve. Controlling the suit air supply thus consisted of adjusting the pressure regulator to a desired pressure level and adjusting the 3/4-inch exit valve to provide the subject with a desired flow.

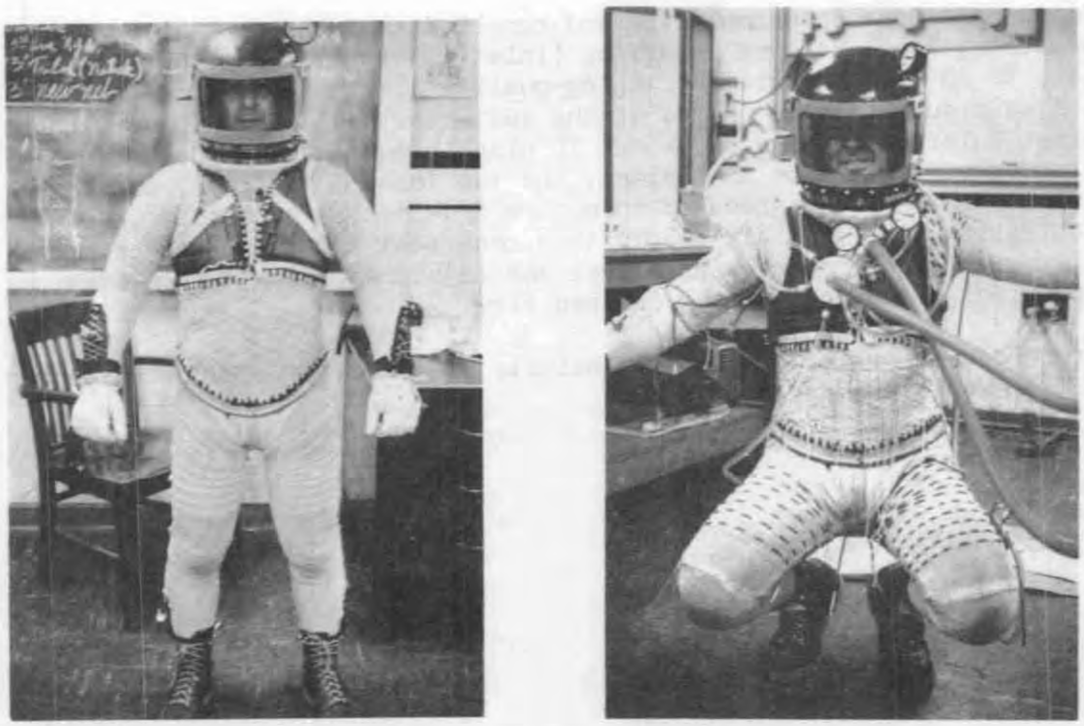
Pressure gages were mounted in the helmet, at the outlet, and at tee connections at the wrist and shin.

OVERALL SUIT ASSEMBLY

The general appearance of the entire suit assembly may be noted in a series of photographs included to indicate, as far as is possible in still pictures, the mobility that was achieved by applying these principles. The pictures are examples from the current state of development, taken at random, whenever various successful elements were added to the assembly. Viewed as a culmination of the development of ideas from their onset in 1950 and as an example of the seventh such prototype in a series of ten (the tenth being operational), they indicate that, in principle and in practice, a pressure suit of great mobility can be developed by the application of physical and anthropological principles. Greater mobility is well within the present knowledge, and simply requires considerably more effort and greater attention to detail.

Figure 13 shows a subject in an unpressurized suit, (a) standing erect in the suit, and (b) performing a deep-knee bend. The figure shows a front view of the assembly and the general nature of the crotch mobility, and depicts how lines of nonextension are used in the crotch.

Figure 14 is presented as the first of a series of illustrations of mobility of the major joints and joint complexes that are problem areas of pressure suit design; the waist, shoulder, and pelvis. Figure 14 shows a subject, (a) standing erect in the suit with no pressure, and (b) bending in a pressurized condition (3 psi).



a. Standing erect

b. Performing deep-knee bends

Figure 13

Subject in an Unpressurized Suit

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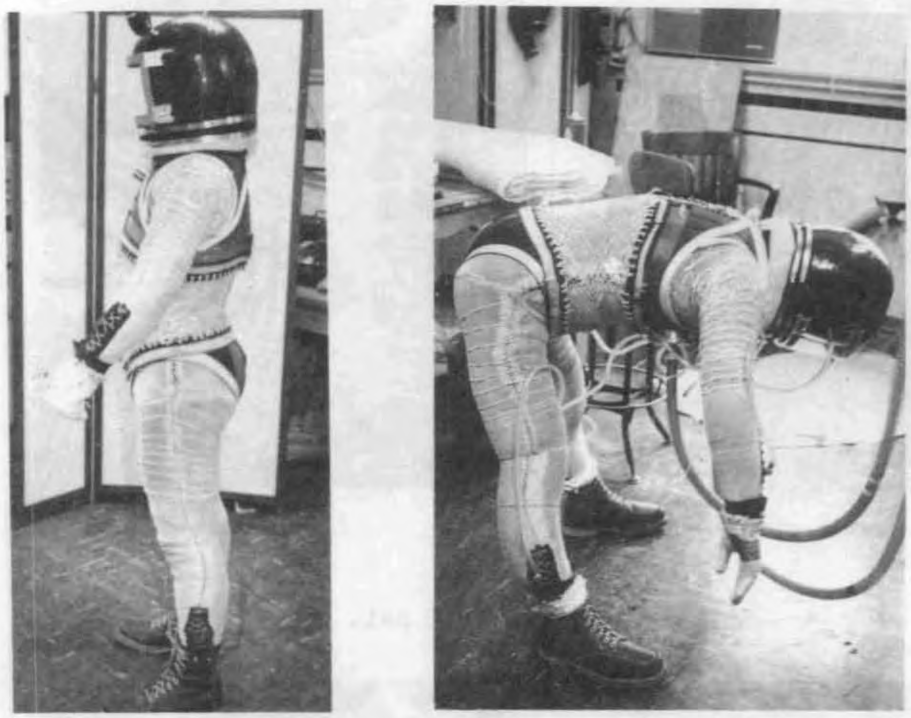
Front and back views of the suit under 3 psi pressure are shown in figure 15. Overhead arm capability with and without pressure is shown in figure 16. Deep-knee-bend capability, squatting capability, sitting capability, kneeling capability, all at 3 psi, are shown in figure 17. Jumping capability and writing capability at 3 psi are shown in figure 18.



a. Standing erect at no pressure

b. Bending at 3 psi

Figure 14

Subject under unpressurized and pressurized conditions

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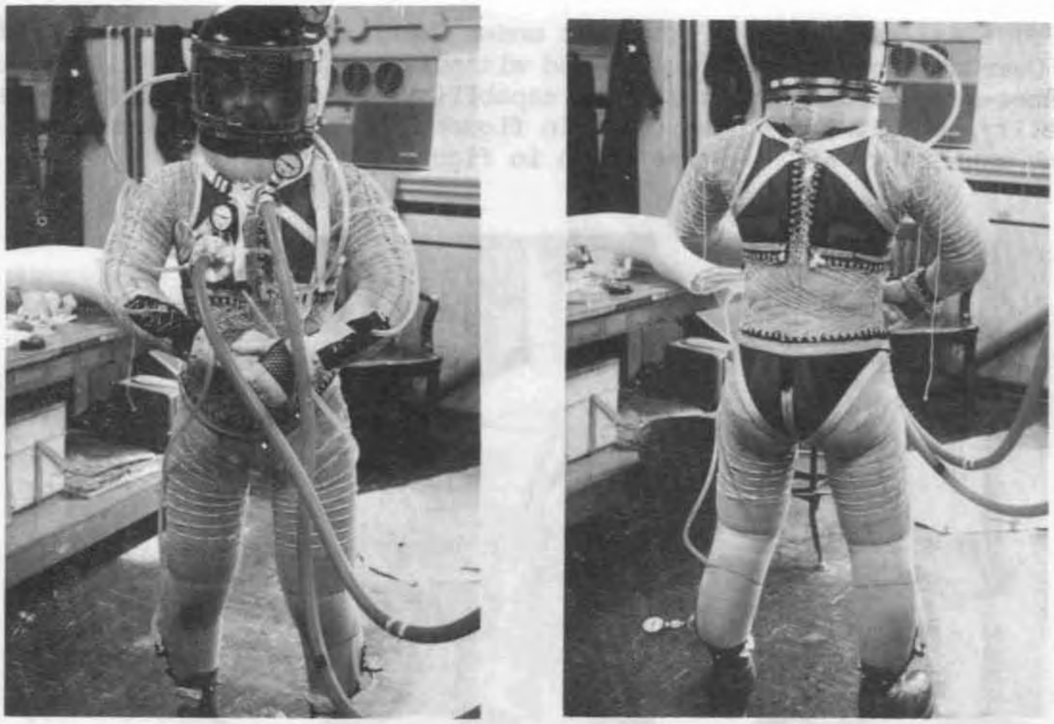
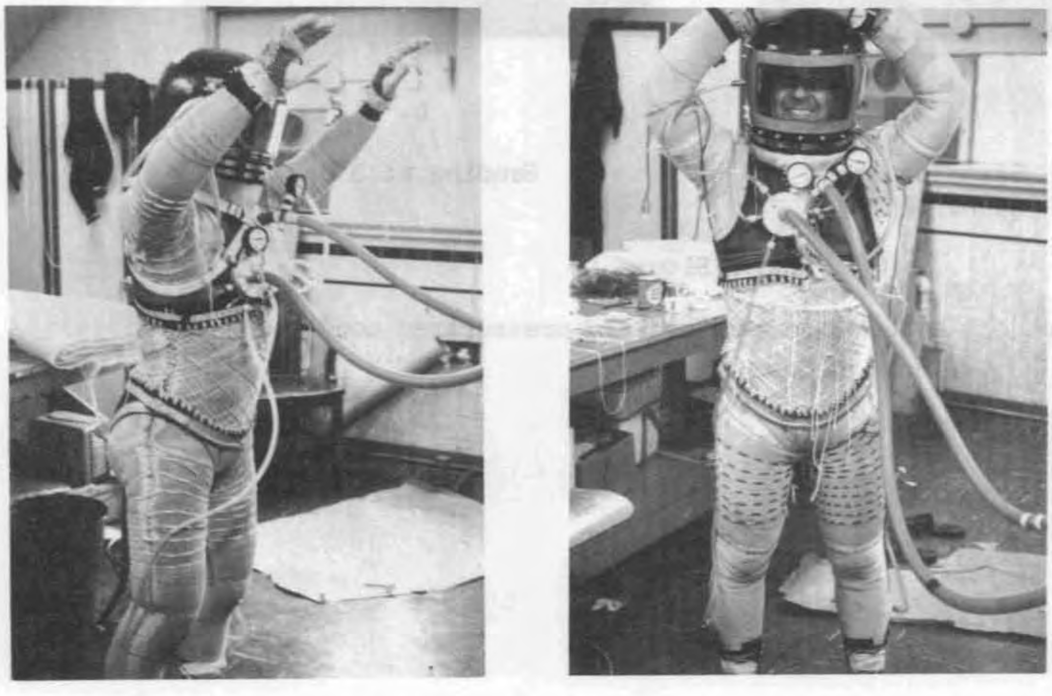


a. Front view b. Back

Figure 15

Suit Pressurized to 3 psi.



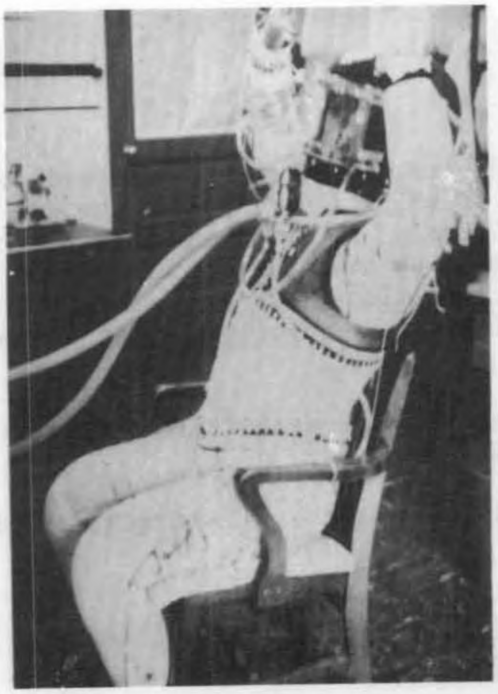
a. Pressurized to 3 psi. b. Unpressurized

Figure 16

Overhead Arm Capability Under Pressurized and Unpressurized Conditions

a. Knee-bends

b. Squat



c. Sit

d. Kneel

Figure 17

Subject Performance at 3 psi.

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a. To jump

b. To write

Figure 18

Capability of a Subject at 3 psi.

At the Aerospace Medical Research Laboratories, measurements were made of the shoulder mobility of the Rand subject (A) in shirt sleeves, with the garment on and vented and then pressurized to 3.75 psi. The decrement to the mobility of the shoulders, as expressed by comparing grasping-reach envelope volumes for the shirt-sleeved and pressurized conditions, was comparable to those caused by wearing the most advanced full-pressure suits available at the time.

The general theory and operation were explained and demonstrated at both unpressurized and pressurized to 3.75 psi conditions.

The mobility demonstrated at pressure consisted of the following types of movements:

bending the elbows
rotating the upper arms through their cones of action
clasping the arms in front of the body
flexing hands and fingers
writing
rotating the waist through its cone of action
walking
rotating the thigh through its cone of action
bending the knee
sitting

squatting
performing deep knee bends
jumping in the air with legs astraddle
jumping in the air with legs scissored

(In a side room, the subject got down on all-fours and then stood upright unaided. He did not do this in the auditorium because the floor was too slippery.)

The suit had been tailored for Subject A; however, it was decided to try the suit on an Air Force subject (hereinafter referred to as Subject D) who had worn all or nearly all types of Air Force pressure suits. The demonstration was undertaken to determine if a suit tailored for one subject could be immediately wearable by another person without many fitting adjustments.

During the development, the subject in the suit changed from Subject C, whose height and weight were 70-1/2 inches and 180 pounds, to another subject whose height and weight were 73 inches and 168 pounds, with no change in the first experimental garment. When a second version of the net suit was made (with improved net material), it was made for A with practically no change in the pattern for the torso. Some shortening in the arms and legs, however, was necessary in the net and vent suits. Subject A was 65 inches tall. Subject D was about 66-1/2 inches tall. Subject D's arms and legs appeared to be somewhat longer than those of Subject A. Thus, the concern was with regard to the fit over Subject D's arms and legs. The project monitor felt that, with regard to sizing in the torso region, the most important dimension was vertical trunk circumference (the torso circumference under the crotch and over the shoulder).

The suit fitted Subject D quite well with no modifications or adjustments, and he accomplished a number of body movements in familiarizing himself with the garment. He made several trips back and forth on a "Force Measuring Walkway" with the suit pressurized to 3.7 psig. Two hours elapsed from the time of the decision to try the suit on Subject D to the time he was dressed and pressurized.

Figure 19 shows Subject D performing body movements. Subjective comfort impressions of Subject D are as follows:

"When I am completely dressed, the suit impairs my breathing, because of its tightness. Some relief can be obtained by bending over and raising the shoulders and arms. Other areas of discomfort were under the arms and over the shoulder blades. Even though suit donning required about 2 hours, I remained comfortable, temperature-wise, though no vent air was passing through the suit. Pressurizing to about 1/4 psi expands the garment, correcting the breathing difficulty but not the tightness under the arms. At 1 psi, the tightness under the arms was gone, and the suit was very comfortable at all higher pressures, including the highest elected pressure, 4 psi.

"Subjective mobility analysis comments follow:

Easy to maintain balance while walking or standing
Excellent bending at the waist
Excellent bending at the knees

Very good shoulder mobility
Excellent twisting of 'torso-waist' area
Very good elbow bending; some pinching occurred
Good sit-stand capability
Poor wrist mobility
Negligible helmet rise

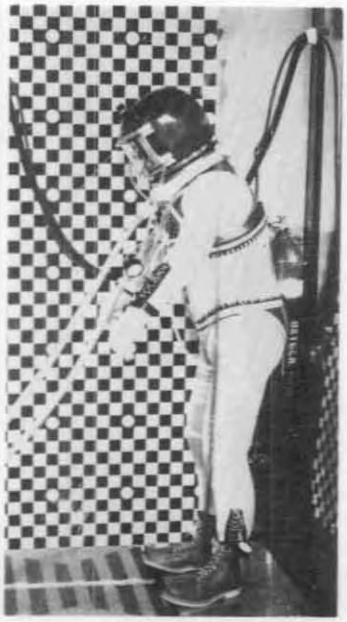
"Though the garment provides comparative ease of movement and the ability to hold the assumed position, when one relaxes, the suit returns to a neutral position. Also, the elbows cannot be held tightly against the sides of the suit torso.

"Throughout the demonstrations, the ventilation distribution system was very effective in maintaining thermal comfort."

a. Unpressurized

b. 2 psi

c. 3 psi



d. 3.75 psi

e. 3.75 psi

f. 3.75 psi

Figure 19

Demonstrations by Subject D (Unpressurized and at Various Pressures)

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Subject D commented that while pressurized he felt "secure" in the suit, without any feeling of "floating" inside of it. Thus, it is apparent that the expense of following the lines of nonextension can achieve a suit that is dynamically and statically form-fitting.

The demonstration showed that any type of body mobility desired in a pressure suit, at least in the range 0 to 5 psi, and likely 0 to 7 psi, can be provided by the use of the principles previously developed by the principal investigator.

One complaint that subjects had was against the excessive tightness of the longitudinal restraint layer about the chest and waist. This resulted from the zeal of the investigators to take out longitudinal extension. As soon as a minute amount of pressure was put in the suit, this tightness disappeared. Subjects A and D demonstrated at AMRL that the pressure required to take this extra-tight lacing load off the torso was about 2 to 3 inches of water, and thus represented unnecessary tightness, rather than necessary restraining spring force required to make the suit work. When Subject A later donned the suit, the lacings for the chest were relaxed a little, and the crushing feeling disappeared.

MATERIALS AND FABRICATION PROCEDURES

LINES OF NONEXTENSION NETS

Having established the lines of nonextension and having transferred them to an anthropological sizing manikin, patterns were cut in accordance with these lines - first with a coarse decorative fish-net for practice, and then with a Dacron net with about four diamonds to the inch. This net was procured from a local knitter, one of a considerable number of suppliers who can knit net. The major requirements are that high-strength yarn be used (the thread used is two-ply, 1100-denier yarn), that a sufficient amount of Dacron be packed into the strand (5000 denier or more), and that a very tight knitting be used. It is desirable that the strand strength be 50 lb per strand or higher.

RUBBER SUITS

Two half-body molds were commercially developed for fashioning the rubber suits. A natural latex rubber was obtained, suitably compounded for oxidation and tear resistance, in about 0.012 inch thickness. The two halves of the suit were designed to be slipped on the subject and sealed by folding at the waist.

UNDERGARMENTS AND SLIP GARMENT

The functions of underwear layer and the slip layer covering the rubber suit were satisfied by commercially available dance leotards.

VENT SUIT

The vent suit was made from a commercially available industrial spacer material.

RUBBER SUIT OUTLETS

The rubber suit outlets were made from large tire-valve patches, reamed out and cemented to the rubber suit; and the large outlet was adapted from an "air bag stem".

LONGITUDINAL RESTRAINT GARMENT

The longitudinal restraint garment (see figure 12) was laid out from straps of nylon sewn side-by-side.

The waist slip-net consisted of 160-lb-test, braided nylon "masons" line, that was looped back and forth between the pants and vest sections. They were run through helical lacings attached to the two sections in a permanent array. This layer opens in the back of the chest section, and must be laced. It can also be zippered for more rapid donning and doffing.

HELMET

The helmet was made of fiberglas-polyester molded on a form.

ACCESSORIES

Work shoes were procured from an Army-Navy surplus store.

Gloves used consisted of thin kid dress gloves, which were covered over with the same netting used in other parts of the suit. A rigid palm section was made, first of hammered, perforated, sheet steel, and then one which was made of heavy steel wire. In the former case, the restraining form was outside, but attached to the glove. In the latter case, the restraining form was covered with cloth. Finger joints were retained, crudely, by glass-reinforced Mylar tape.

RECOMMENDATIONS FOR AN OPERATIONAL TYPE FULL-PRESSURE SUIT

The logic of the current development followed very strictly on the findings reported in reference 2, which in turn, followed from foundations laid in reference 1.

The next steps involved the research and development of practical forms and materials.

The end objective is a total integration of suit layers into a manufactured complex to meet the operational requirements. This will have to evolve through a number of stages. In the originally estimated nominal sequence of ten progressive suits, the suit described herein is considered the seventh. There remain then, about three suits required to perform the necessary research and development in materials and in the preferred integrations of form and function. At this point, the immediate recommendations can be projected only to the development state that should be reached in the next phase.

The leotard-type of underwear layer is satisfactory.

The vent suit made of a fairly rigid spacer material, with a collapsing diamond action, is satisfactory. However, it may not have much bending resistance, since the collapse required in such regions as the arm pit must be considerable. It should be softly but porously padded on its inner surface. Thus one development could be of an underwear layer of the vent type, or one layer that combines the function of underwear and vent. In the latter case, a single "underwear" layer may be visualized as being a distinctly personalized layer for personnel likely to use pressure suits. It may be donned simply, like long underwear, and closed with a few zippers.

The air retaining layer is at present the most unsatisfactory item in the development. A thin rubber layer works. Thin rubber has been combined with other independent or combined cloth layers, but the solution is not really satisfactory. A desirable solution would be a highly creped or stretchy impervious material that can make a comfortable, easily stretched body covering, that has high integrity, that is impermeable to gas pressure, and that has high puncture resistance. An ideal material would possess the puncture resistance and toughness of an inner tube, but with less thickness. Present requirements have been met through the use of a thin rubber suit covered by a tough, stretchy, knitted garment. Significantly better solutions will take serious research effort. For example, to understand how low the stretching forces must be in such a layer, note that previous effort (ref 2) demonstrated that a total suit covering made from power net, the common girdle material, was unbearable to the wearer.

These difficulties indicate that it is illusory to wonder what layers can be integrated with the rubber layer. If a real rubber-layer solution is developed or forthcoming, then its integratability can be considered. Currently, the rubber layer is still viewed as an independent layer, that is, a "second" layer. It can be easily slipped on in an upper and lower part, with a simple seal at the waist.

A one-piece, lines-of-nonextension net complex could be manufactured. This could be donned moderately easily. Closures would be zippers, similar to the vent suit, at the back, wrists, and ankles. This would constitute a third layer. At some future time, this complex could conceivably be integrated with the impervious rubber and vent layers.

The longitudinal restraint complex is currently viewed as an independent fourth layer. It could be developed so as to be easily donned, with one zipper closure in the back.

Gloves, shoes, and helmet represent similar problems of attaching a net-complex covering, that is, a "leather-like" covering, or "rigid" covering to the net complex.

There is one important point to note. The availability of a full set of guiding lines of nonextension, and the study, time and time again, of a careful division of layers has resolved the problem of closures (see ref 2). Simple zippers may now be employed.

These comments should not be regarded as a total solution of all problems. A number remain:

There is a sizing problem. Although it is no problem to establish specific sizes for the uninflated pressure suit to cover a using population, the pressurized suit tends to elongate. The necessity to restrain the helmet, gloves, and shoes introduces complications to any sizing system for the pressurized suit. How conformal do these garments have to be? The best answer seems to be that the wearer should be pleasantly conscious of the suit, and feel snug in it. In the past the author has attempted to construct these close-fitting garments according to a specification for a 1/16 to 1/4-inch stand-off from the body. It appears that there is a need for an adjustment in which a standard garment is taken up by the wearer to become conformal and fitted for him. There are at least three suitable take up techniques involving strategic lacings, belts, or pressurized capstans which might make the adjustments automatically.

There is the problem of thermal control. The current solutions toward a determinate porous spacing for pressure equalization, as shown in the vent suit, appears suited for this need. The problem remaining turns to removal of the heat loads while working, or in warm environments. Studies indicate that one must be concerned with the transient heat load in a confined volume like a pressure suit. Thus a rapid heat exchange is required. Gas exchange does not appear to be the best solution, although it has been employed, because it is simple to use in the laboratory where one can dump a large quantity of ventilated air through a suit. The thermal dynamics of the human, both in quiescence and activity, involve rapid changes of the order of a 2- to 10-fold increase of metabolic heat over basal metabolism in periods of a few minutes. Experiments at the Bureau of Standards demonstrated the validity of using liquid exchangers.

With this suit foundation, representing as it does a complete and unique solution to the pressure-mobility problem, it should be possible to go on to the other pressing operational requirements in protective coverings for the human.

SUMMARY AND CONCLUSIONS

Following the theory of a pressure suit having high mobility, which has been described in earlier efforts:

A complete set of lines of nonextension has been determined from three subjects; and these lines have shown themselves to be quite general for the human form.

A net suit, patterned piece-by-piece from a woven high-strength Dacron net with constant-sized diamonds, has been constructed as a form-fitting, load-bearing garment for a medium-sized subject. The conformity of this suit to the body, during all body deformations, is quite excellent.

A thin (approximately 0.012 inch) rubber suit has been fabricated, by dipping on a three-dimensional form, to be conformal with a human body.

Conformal high-strength and nonstretching cloth garments have been fabricated for the chest (as a vest) and pelvis (as very brief shorts) and laced together with a slipping-string net pattern.

The combination of a gas-retaining rubber layer, a load-bearing net layer that follows the lines of nonextension, and a slip-net structure in the waist, forms a pressure-retaining, form-fitting garment capable of providing easy and natural mobility of all body joints, both with and without pressure, with minimum ballooning under pressure. This has been demonstrated in the 0 to 5 psi range above ambient pressure.

Easy mobility has been demonstrated for the following types of motions:

- bending the elbows
- rotating the upper arms through their cones of action
- clasping the arms in front of the body
- flexing hands and fingers
- writing
- manipulating hand tools
- rotating the waist through its cone of action
- walking
- rotating the thigh through its cone of action
- bending the knee
- sitting
- squatting
- performing deep-knee bends
- doing push-ups
- jumping in the air with legs astraddle
- jumping in the air with legs scissored
- getting down on all-fours and standing up, unaided

In greater detail, the functional layers of the suit include:

An underwear layer to absorb perspiration and to prevent body chafing.

A vent suit made of a fiber-like industrial spacer material, which was also patterned to follow the lines of nonextension, to equalize pressure over the body surface and to permit passage of heat-exchanging and ventilating air through this porous spacing layer.

A thin rubber suit to permit body mobility and yet retain pressure.

A stretchy knitted-cloth layer to protect the thin rubber against cuts, tears, and penetration, and to provide some slip against pinching.

A high-strength net suit that follows the lines of nonextension. This layer retains loads developed in the rubber suit by the internal pressure, completely in the circumferential and radial direction (ie against ballooning) while permitting mobile deformation of the joints, and restrains most, but not all, of the longitudinal deformation in the pressurized suit.

A cloth vest and pants that are laced together by what is considered to represent a "slip-net." This constraint limits the rest of the longitudinal deformation that is otherwise restrained by the lines of nonextension net only with great difficulty.

Conventional high-laced work shoes are provided, although special-purpose, lightweight shoes involving the same netting principles could be developed.

Conventional dress gloves are used and are restrained by similar netting principles, with a rigid constraint over the palm to prevent ballooning. For finer, more complete fingers and hand mobility, a much greater detailing of the hands by the same principles as are used in the rest of the suit is necessary.

A fixed, rigid, slip-over helmet was constructed to demonstrate the smallest slip-over sized helmet that could be used, and to illustrate the degree of conflict and compromise that it poses to shoulder mobility.

For demonstration purposes, an external distribution system carries ventilation air into the suit at the chest and helmet and away from the suit by a spider manifold of tubes connecting to both ankles, both wrists, and the helmet. This further assures uniformity of pressure for test purposes.

Having completed the theory of operation, and fully demonstrated its experimental feasibility, there remains the task of engineering research and development of most suitable materials, and a structural integration of layers into a possible operational suit. Such research and development is required before a meaningful procurement specification for an operational suit can be developed.

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13. ABSTRACT

An important objective in the development of a full-pressure suit for a human being is to permit the wearer full mobility without interfering with physical capability. Although the human skin is stretched during body motion, there is virtually no stretch along certain lines, here called "lines of nonextension." This investigation was undertaken to determine the efficacy of utilizing lines of nonextension to provide natural mobility and minimal ballooning in full-pressure suits. The program of investigation pursued was: (1) to map out these lines of nonextension, (2) to test whether string elements of high elastic modulus, a connected network, could be laid along these lines of nonextension without providing any constraint to mobility, (3) to obtain a highly mobile pressure-retaining layer to be constrained by the net, and (4) to construct and demonstrate an entire pressure-retaining garment system that makes use of all necessary layers and string elements in a completely connected, netted covering for the body, with minimal constraint to mobility up to 5 psi. The technique, result, and collateral observations relevant to each of these phases are described. A mobile, pressure-retaining garment was developed by building each structural, functional layer into the composite garment in accordance with the basic design theory.

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